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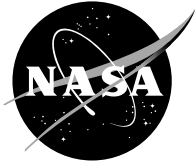
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200 °C DEMONSTRATION TRANSFORMER OPERATES EFFICIENTLY AT 50 kHz

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ABSTRACT

A compact, high temperature demonstration transformer was constructed, using a moly permalloy powder core and Teflon-insulated copper wire. At 50 kHz and 200 °C, this 1:2 ratio transformer is capable of 98% efficiency when operating at a specific power of 6.1 kW/kg at 4 kW. This roughly 7 cm diameter transformer has a mass of 0.65 kg. Although Teflon is unstable above 200 °C, about the same electrical performance was seen at 250 °C. A plot of winding loss vs. frequency illustrates the need to control these losses at high frequency.

COMPACT HIGH TEMPERATURE TRANSFORMER OPERATES EFFICIENTLY AT 200 °C

Readily available magnetic and wiring materials suitable for use at elevated temperatures were used to construct a transformer that demonstrates the consequences of pushing these materials beyond their conservative temperature ratings. The critical elements above 200 °C are the magnetic material and wire insulation. The present transformer was based on a moly permalloy powder (MPP) core wound with Teflon insulated copper wire.

Commercial MPP cores are normally not rated for operation above about 140 °C, although they are regularly equipped with 200 °C coatings. Their intrinsic magnetic material, being roughly 80-20 % Ni-Fe, is known to have good soft magnetic characteristics up to 300 °C. But the properties of the binder material may be expected to have a deleterious influence at such high temperatures. Occasional measurements at NASA Glenn indicate that over short durations (hours, not thousands of hours) certain MPP cores have nearly the same core loss and inductance at 250 °C as at 23 °C. Long-term stability under high temperature is unknown.

Above 200 °C, no wire insulation is known that is compact, has a high dielectric strength, and is stable and mechanically durable. Ceramic beads or sleeves may be acceptable in high frequency designs that can use relatively few turns of winding. Such windings have been used to characterize Supermendur up to 900 °C in a NASA magnetic materials testing program.

Teflon insulation was chosen here, for its good dielectric strength and ease of winding. Indeed, Teflon film is used as the dielectric in some commercial, hermetically sealed capacitors rated up to 200 °C. Above 200 °C, Teflon materials start to outgas rapidly and soften and hence would not be suitable for long duration aerospace applications at such temperatures. However, in the present, short-duration demonstration tests, Teflon insulation served quite well to 250 °C.

Using Teflon insulated windings on an MPP core, 98% efficiency was shown to 250 °C, for a 1:2 ratio transformer capable of power densities over 6 kW/kg, when operated at 50 kHz. This is all fairly predictable and nothing new was found. Nevertheless, the demonstration reviews an important point regarding the distribution of core and winding losses at high frequencies.

CONSTRUCTION

Two type 55106-M4 (Magnetics Division of Spang) MPP cores were stacked to give a core having the following properties:

$A = 2.89 \text{ cm}^2$	(core cross-section)
$m_c = 352 \text{ g}$	(core mass)
$\bar{\ell} = 14.3 \text{ cm}$	(mean path length)
$\rho = 8.54 \text{ g/cm}^3$	(core density)
$V = 41.2 \text{ cm}^3$	(core volume)
$\mu_r = 200$	(relative permeability)

This stacked core was then equipped with 3 windings of Teflon insulated (rated 1000 V), stranded copper wire:

$N_1 = 20$ turns, about 10 AWG, MIL-W-22759/12-10, $R_{dc} = 0.0125 \Omega$

$N_2 = 40$ turns, about 16 AWG, MIL-W-22759/12-14-9, $R_{dc} = 0.043 \Omega$

$N_s = 20$ turns, 20 AWG

In use, N_1 was the primary winding, N_2 was the secondary winding and N_s served as a sense winding for the induced voltage. The winding mass, including foot-long leads, is 0.298 kg, making up a total mass of

0.65 kg for this transformer. With windings, the overall diameter is roughly 7 cm.

EXPERIMENTAL DATA

Using a previously developed digital power measuring setup [1, 2, 3], three types of measurements were made at 50 kHz and selected temperatures: core loss, winding loss, and input and output powers under a resistive load. Reduced data is presented in Table I and the particulars of each measurement are discussed below. It should be remarked that for the sake of temperature stability, the sinusoidal excitation signal was applied in 1 ms long bursts, about once a second. This 0.1% duty cycle averted the problem of having to cool the load resistor.

Core loss

For core loss measurements, N_1 was used as the excitation winding and N_s was used to sense the induced voltage V_s . The time integral $V_\phi(t)$ of $V_s(t)$ was used to accurately set the peak B-field B_p , according to

$$V_{\phi,p} = N_s A B_p, \quad (1)$$

for this formula is valid even in the presence of waveform distortion and is independent of frequency. The core loss values entered in Table I are specific to B_p of 0.10 T, as set by this method, with N_2 open circuited. With the load connected, the input voltage could be adjusted to give approximately the same B_p by monitoring $V_{\phi,p}$ or $V_{s,p}$; however, there may be some unavoidable error then, due to the load current interacting with the leakage inductance. Note that the specific core loss in Table I is less than 0.4 W/cm³ for all cases shown.

Winding loss

The dc resistances of N_1 and N_2 were measured to be 0.0125 Ω and 0.043 Ω , respectively. However, at high frequency, the ac resistance is substantially increased by the proximity and skin effects. The only easy way to measure these resistances in-situ is to measure a combined equivalent loss resistance R_{eq} by means of the short-circuit test (i.e., with N_2 short circuited). R_{eq} is thus computed from the measured power input and current. The values for R_{eq} entered in Table I are for a primary current of about 20 A rms, which is conservative for the 10 AWG wire size.

In a simple model of a transformer, R_{eq} referred to N_1 is given by

$$R_{eq} = R_1 + (N_1 / N_2)^2 R_2, \quad (2)$$

in terms of the primary and secondary ac resistances. Such simple modeling is not entirely accurate for the present hardware, as R_{eq} was found to have a significant dependence on the current. This somewhat unusual behavior seems most likely due to interactions with the magnetic core. That is, leakage inductance voltage drops may be exciting the core sufficiently to make for an observable core loss contribution, even under short-circuit tests. The copper loss contribution in Table I is based on the load current flowing through the measured R_{eq} and is hence an indirect estimate of that loss under load. It may be possible to separate out residual core loss contributions by using information from V_s , but this has not been investigated.

Figure 1 shows the observed anomalous dependence of R_{eq} on the current. Plots are shown versus frequency for peak currents of 10 and 20 A. The curvature reversal at lower frequency, followed by a rise at decreasing rate, is characteristic of the skin effect. Hence this is evidence for the benefit that a Litz type wire (twisted bundles of insulated fine strands) would have here in reducing copper losses.

Loaded transformer

A 25 Ω , 1 kW, load was made by parallel connecting four 100 Ω , 250 W, non-inductive, wire-wound resistors. This load was quite safe, should for some reason the 0.1% duty cycle, 2.6 kW burst mode suddenly go into a continuous mode. As measurements were made at the selected temperatures, the $V_{s,p}$ was monitored to a constant value that corresponds to B_p of 0.10 T in the no-load case. The (cycle average) input and load powers entered in Table I could not be measured simultaneously, for lack of a sufficient number of recording channels. Hence these powers had to be measured sequentially, using V_s as the control reference. This method was not sufficiently stable to resolve the roughly 2% losses from direct measurements of the input and load powers. Hence the efficiency had to be based on best estimates of the losses under load, based on separate measurements, as per above discussion. The ‘bottom line’ of Table I is that a 98% efficiency was observed from 23 to 250 $^{\circ}\text{C}$, with 2.6 kW delivered to the load.

SUMMARY AND DISCUSSION

A compact, high temperature, 1:2 ratio transformer has been constructed from commercially available moly permalloy powder (MPP) cores and Teflon insulated copper wire that can maintain 98% efficiency to temperatures exceeding 200 $^{\circ}\text{C}$. With peak B-field in the core limited to 0.10 T at 50 kHz, a specific power

handling density of 4.05 kW/kg was observed when delivering 2.6 kW to a resistive load.

At the above conditions and over the temperature range of 23 to 250 °C, the core loss varied from about 12 to 16 W, whereas the winding loss varied from about 40 to 50 W (see Table I). The relatively high winding loss is due to the already heavy influence of the skin and proximity effects at 50 kHz. The lesson of this (see figure 1) is that to avoid the predominance of winding losses at high frequency, either the winding volume must be reduced and the magnetics utilization increased (bigger core cross-section or higher B_{peak}), or the wire should be of the Litz type. Equivalently, the rated voltage can be increased to the point where the core loss is comparable to the winding loss. This can significantly up-rate the power without sacrificing the efficiency. Thus the specific core loss in the present case is only 0.4 W/cm³, which could be safely increased by a factor of 3. According to the manufacturer's data for the present MPP material, going to a B_{peak} of 0.15 T at 50 kHz would provide the factor of 3. This also increases the input voltage, and hence power, by a factor of 1.5. Using the 200 °C data from Table I, the efficiency is

$$\epsilon = 1 - \frac{45 + 3 \times 12.4}{1.5 \times 2640} = 0.98 \quad (3)$$

and the specific power density becomes 6.08 kW/kg. This exercise illustrates the value of a magnetic material having low losses at high B_{peak} , despite the copper loss problem.

Long-term operation of this transformer at 200 °C may be feasible, where the Teflon insulation is not subject to harmful mechanical stresses and where perhaps some outgassing can be tolerated. Although the present design worked as well at 250 °C in short-term tests, Teflon is not normally used at 250 °C in aerospace applications. Also, the magnetic properties of MPP at 250 °C may well be unstable in the long run, since manufacturers do not discuss temperatures above

140 °C for MPP cores. Apart from a single observation of a 5% increase in core loss after the 250 °C runs, no aging study was done.

Worth a passing mention may be anecdotal evidence for a static charging phenomenon involving the Teflon insulation. In high temperature testing, the transformer was placed on a ceramic-topped hotplate and covered with a wad of mineral wool insulation. However, a small aluminum plate was inserted between the transformer and the ceramic top, to even the temperature. Above 200 °C, significant noise spikes of unknown origin were observed on the digitizing oscilloscope. This noise did not appear to be synchronized with the on-off powering of the hotplate. Since during core loss tests the voltage sensing was done differentially, the sense winding was isolated from ground by the high probe impedance. It was discovered that grounding the inserted plate eliminated, or greatly reduced, the noise spikes. The phenomenon may be worth another look, as it might be a static charging phenomenon associated with the outgassing of the Teflon insulation.

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Table 1.—Summary Data for the MPP-Core High Temperature Transformer

T (°C)	I _{1, p-p} (A)	V _{1, p-p} (V)	I _{2, p-p} (A)	V _{2, p-p} (V)	\bar{P}_{in} (W)	\bar{P}_{load} (W)	\bar{P}_{Cu} (W)	\bar{P}_{core} (W)	R _{eq} (Ω)
23	58.5	372.	29.5	728.	2605.	2607.	40.	15.7	0.093
200	59.0	376.	29.5	732.	2640.	2635.	45.	12.4	0.103
250	59.4	379.	29.6	731.	2678.	2634.	49.	15.3	0.113

Notes:

- 1 – Operation is at 50 kHz and $B_p \approx 0.10$ T, using a permeability-200 MPP core equipped with 1:2 turns ratio windings.
- 2 – Efficiency is about 98% for all 3 temperatures. This is calculated from the separately measured core and copper losses.
- 3 – The power factor is below unity, due to leakage inductances. The load is 25 ohms, resistive.
- 4 – The current and voltage values are the peak-to-peak readings given by the digitizing instrumentation.
- 5 – Measurements are described in more detail in the text.

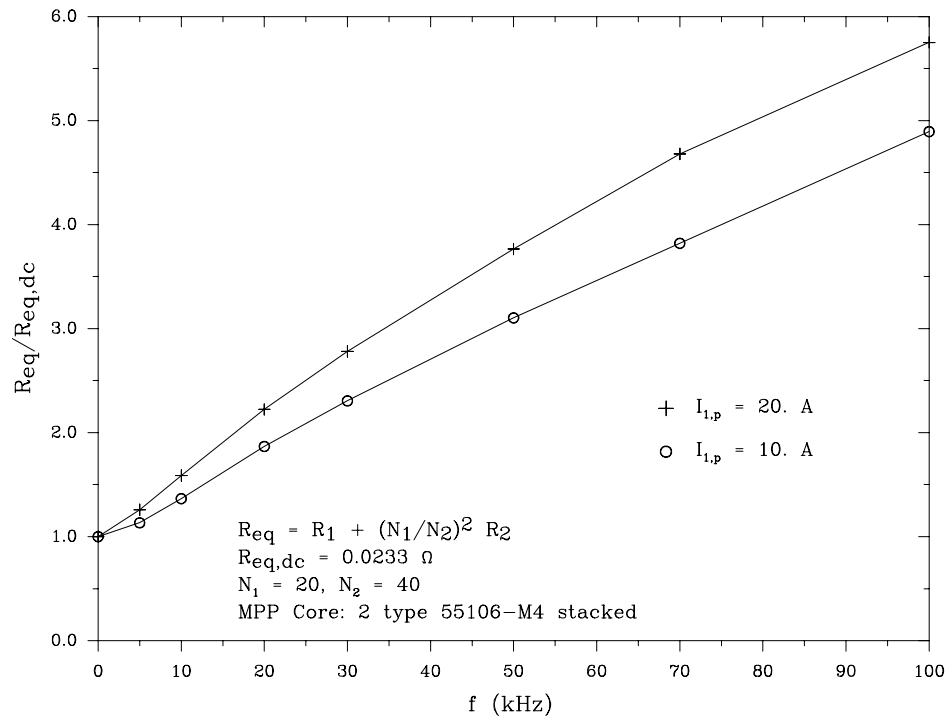


Figure 1. Frequency dependence of the equivalent winding resistance, referred to the primary and normalized to its dc value. R_{eq} was measured by the standard short-circuit test. Plots are shown for 2 selected values of peak primary winding current. The dependence on current may be due to residual core loss.

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